Differential modulations of ipsilateral and contralateral beta (de)synchronization during unimanual force production

van Wijk, B.C.M.; Beek, P.J.; Daffertshofer, A.

published in
European Journal of Neuroscience
2012

DOI (link to publisher)
10.1111/j.1460-9568.2012.08122.x

document version
Publisher's PDF, also known as Version of record

EJN fens European Journal of Neuroscience

European Journal of Neuroscience, Vol. 36, pp. 2088–2097, 2012 doi:10.1111/j.1460-9568.2012.08122.x

NEUROSYSTEMS

Differential modulations of ipsilateral and contralateral beta (de)synchronization during unimanual force production

B. C. M. van Wijk, P. J. Beek and A. Daffertshofer
Research Institute MOVE, VU University Amsterdam, Amsterdam, The Netherlands

Keywords: beta power, corticospinal synchronization, interhemispheric facilitation/inhibition, motor cortex

Abstract

Unilateral movement is usually accompanied by ipsilateral activity in the primary motor cortex (M1). It is still largely unclear whether this activity reflects interhemispheric 'cross-talk' of contralateral M1 that facilitates movement, or results from processes that inhibit motor output. We investigated the role of beta power in ipsilateral M1 during unimanual force production. Significant ipsilateral beta desynchronization occurred during continuous dynamic but not during static force production. Moreover, event-related time–frequency analysis revealed bilateral desynchronization patterns, whereas post-movement synchronization was confined to the contralateral hemisphere. Our findings indicate that ipsilateral activation is not merely the result of interhemispheric cross-talk but involves additional processes. Given observations of differential blood oxygen level-dependent responses in ipsilateral and contralateral M1, and the correlation between beta desynchronization and the firing rate of pyramidal tract neurons in contralateral M1 during movement, we speculate that beta desynchronization in contra- and ipsilateral M1 arises from distinct neural activation patterns.

Introduction

The organization of the human motor system is largely symmetric. Most corticospinal pathways transect in the pyramidal decussation, resulting in a predominantly contralateral cortical motor control. Nevertheless, left and right pathways are anatomically connected at various levels along the neural axis: through the corpus callosum; via non-crossing corticospinal fibers; and in the spinal cord. Although these left/right connections may facilitate the coordination of bimanual movements, activity is not limited to the contralateral hemisphere when performing movements with one hand only. Activity in ipsilateral motor areas is known to accompany unilateral movement (Kristeva *et al.*, 1979, 1991; Babiloni *et al.*, 1999; Baraldi *et al.*, 1999; Huang *et al.*, 2004; Gross *et al.*, 2005), and its strength correlates with task complexity (Salmelin *et al.*, 1995; Manganotti *et al.*, 1998; Hummel *et al.*, 2003; Verstynen *et al.*, 2005).

Why ipsilateral primary motor cortex (M1) is involved in unimanual tasks is still largely unclear. Does this activity result from projections between bilateral areas, giving rise to a mere 'cross-talk' of contralateral M1 activity that may facilitate movement? Or does it reflect distinct processes related to the prevention of involuntary movements, i.e. inhibition of cross-talk? Interhemispheric cross-talk seems particularly functional when performing symmetric, bimanual movements, which require less cortical activation than asymmetric bimanual movements (Sadato *et al.*, 1997; Stephan *et al.*, 1999; Immisch *et al.*, 2001; Gross *et al.*, 2005). If unilateral performance is desired, however, ipsilateral M1 activity should not induce movements of the homologous limb. In this case the (crossed) output of the ipsilateral cortex to the spinal cord has to be suppressed. A candidate mechanism for this is interhemispheric inhibition, which is effectuated through excitatory transcallosal connections projecting on local inhibitory interneurons (Carson, 2005). Improper suppression of contralateral motor activity may lead to mirror movements (Armatas *et al.*, 1994; Daffertshofer *et al.*, 1999; Mayston *et al.*, 1999; Aranyi & Rosler, 2002; Hoy *et al.*, 2004; Cincotta & Ziemann, 2008; Hubers *et al.*, 2008) and transitions in rhythmic bimanual coordination (Daffertshofer *et al.*, 2005; Aramaki *et al.*, 2006; Houweling *et al.*, 2010).

The aim of the present study was to investigate the role of ipsilateral beta activity for unimanual static and dynamic force production. Dynamic tasks may be more demanding as they require continuous adjustments of motor output. One may therefore expect enhanced cross-talk during dynamic force production, possibly resulting in stronger ipsilateral activity. In fact, Gross *et al.* (2005) found a stronger ipsilateral involvement of M1 during dynamic compared with static performance. In contrast to their study, we opted for simple, non-rhythmic dynamic force production tasks to minimize activity in sources other than bilateral M1 as they might hamper a clear-cut interpretation. We hypothesized that ipsilateral beta activity not only results from interhemispheric cross-talk but also reflects neural processes needed to prevent mirror movements. In case of mere cross-talk, its dynamics should follow an activity pattern that, alterations in strength aside, agrees with that of its contralateral counterpart. We therefore also compared ipsilateral and contralateral movement-related beta desynchronization (ERD) and synchronization (ERS).

Correspondence: B. C. M. van Wijk, as above.
E-mail: b.c.m.van.wijk@vu.nl

Received 5 December 2011, revised 14 March 2012, accepted 14 March 2012

Materials and methods

Participants

Twenty healthy participants (11 male, 22–35 years old) volunteered in the experiment. They were all right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971), and had normal or corrected-to-normal vision. The local ethics committee had approved the experiment, and written informed consent was obtained from each participant prior to recordings. The experiments were conducted in accordance with the Declaration of Helsinki. Data from one participant were excluded for further analysis due to technical problems during the recordings.

Experimental procedure

Participants performed static and dynamic grip forces in a seated position while their brain activity was recorded using a 151-channel whole-head magnetoencephalography (MEG) system (CTF Systems, Vancouver, BC, Canada) with third-order synthetic gradiometers. Force was exerted either uni- or bimanually by squeezing with each hand separately an MEG-compatible compliant force sensor between the thumb and index finger, while the lower arms were resting on the chair. Surface electromyographs (EMGs) were obtained from left and right first dorsal interosseous, flexor pollicis brevis and flexor digitorum communis muscles. Signals were sampled with a frequency of 1.25 kHz after low-pass filtering at 400 Hz. Online visual feedback was provided on a screen in front of the subjects by means of two adjacent bars of in-/decreasing height on which the target force was indicated as well. Participants were instructed to fixate their gaze on a white dot displayed between the force bars, and to minimize eye movements and blinks during trials.

The experimental conditions were divided into long and short trials of force production (see Fig. 1 for a schematic overview). For the long trials, participants followed a prescribed continuous force pattern for 45 s. Six active conditions were performed: static unimanual-left; static unimanual-right; static bimanual; dynamic unimanual-left; dynamic unimanual-right; dynamic bimanual force production; and a resting state condition during which no force was exerted. The static conditions required the production of a constant force of 3 N. The dynamic force profiles contained a slow build-up and release of force that was unpredictable in timing (build-up/release of 2 or 3 s duration) and peak force (either 1.5 or 3 N), hence being different from rhythmic force generation. The force profiles always agreed for both hands in the bimanual condition. Low target forces (approximately 5% MVC) were chosen in order to avoid muscle fatigue during the experiment. Three trials were performed in each condition. These were presented in three blocks of static and three blocks of dynamic trials in a random order. The resting state trials were placed at the start of the first, third and fifth block. This amounted to a total of 21 trials distributed over six blocks for each subject.

After the continuous force conditions, two short-duration conditions were performed. The prescribed force level for these conditions entailed 3 s rest followed by a 2 s linear increase in force and a subsequent constant 3 N target force for 5 s. These were performed either with the right hand only or bimanually. Both conditions contained 100 trials that were presented in two blocks of 50 trials. A condition performed with the left hand only was omitted for the sake of brevity.

Head localization was measured during the MEG recordings before and after each block using coils on the nasion and pre-auricular points (de Munck *et al.*, 2001).

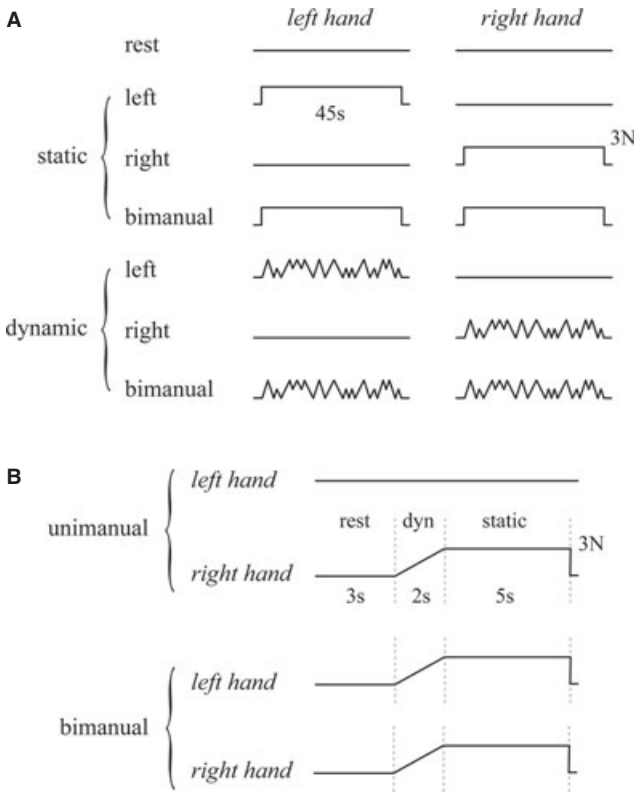

FIG. 1. Overview of all experimental conditions. Schematic representation of force profiles during the continuous force production conditions (A) and the short-duration conditions (B).

Source activity

Regions that were significantly activated in the continuous force production conditions were identified using source localization. Subsequently, the MEG time series were projected from sensor space to source space. The source localization was accomplished with synthetic aperture magnetronomy (SAM) beamformers (Vrba & Robinson, 2001; Hillebrand & Barnes, 2005; Cheyne *et al.*, 2006) using the MEG system's software (CTF MEG Software 5.0). In general, beamformers provide spatial filters that allow for pinpointing spectral power of a pre-selected frequency band in a certain time window. We here concentrated on the results for the beta band (15–30 Hz), as the alpha band (7–11 Hz) turned out to entail highly similar M1 sources, and no significant sources were found for the gamma band (40–70 Hz). The first 5 s of each trial were omitted, which left an active time interval of 40 s over which power was averaged. Our forward model was based on a template structural magnetic resonance imaging (MRI) scan (ICBM152) using a conventional local spheres approximation. A linear transformation was applied to match the average position of the MEG fiducials with corresponding MRI landmarks. Note that for group analysis, the use of a template scan vs. individual MRI scans yields comparable results (Steinstraeter *et al.*, 2009). To identify active sources, each of the active conditions was contrasted with the resting state, which yielded a pseudo-*t*-value for every voxel at $2 \times 2 \times 2$ mm resolution. The so-defined statistical 3D-maps were obtained for each individual and condition. To determine significantly active sources at group level, we used permutation tests with a significance level of $\alpha = 0.05$ (Nichols & Holmes, 2002; Singh *et al.*, 2003). All voxels exceeding this level were considered significant. Within each cluster of significant voxels, the coordinates of the peak pseudo-*t*-value were finally obtained using

a grand-averaged statistical map over all subjects and conditions. The sensor data were projected onto these source locations by a weighted sum of the time series of each MEG channel, as determined by the beamformer weights. In this way, a 'virtual sensor' representing source activity was constructed per subject for all single trials of the continuous force production conditions, as well as the short-duration conditions. All subsequent analyses and results are based on this activity in source space.

Spectral power

The left and right M1s were the only sources that showed significant task-related activity. For the continuous force production trials, the strength of the activity was assessed via the mean beta power in the 40-s active time window. We followed this approach for both sources even if they were not significantly active in the condition under study. Spectral power was computed using 2-Hz frequency bins over the 15–30 Hz interval. Per frequency bin the source time series were filtered (bi-directional second-order Butterworth) and the modulus of the analytic signal obtained via Hilbert transform served as an estimate of spectral power. Subsequently, these power values were averaged over all frequency bins and the 40-s time window to obtain a single measure for the beta band activity. To correct for inter- and intra-individual differences in power levels, we divided the mean power in the active conditions by the corresponding mean power of the resting state. The so-normalized power was subsequently averaged over trials and left and right M1s to obtain separate values for the hemispheres contralateral and ipsilateral to the force producing hand for unimanual conditions, and a single value for the bimanual conditions. A log-transform was applied prior to any averaging to improve normality (Halliday *et al.*, 1995).

The power for the EMG signals was calculated in a similar way after offset removal and full-wave rectification, i.e. the modulus of the analytic signal (Myers *et al.*, 2003). In view of the expected variability of EMG power across trials, we opted for the median rather than the mean over trials. Because EMG power during resting state was low, we normalized the power values per subject by dividing the power for each condition by the sum over conditions. The resulting relative power values were further averaged over the three muscles per arm/hand and over conditions to obtain separate values for the active and passive hand during the unimanual conditions and a single value for the bimanual conditions.

The short-duration trials enabled us to study time-resolved changes in synchronization patterns. Time–frequency spectra were obtained using again the Hilbert amplitude, but now for a frequency range of 5–45 Hz and averaging over trials instead of time. Here the power was normalized per frequency bin via the mean power in the baseline time period without force production (0–3 s) prior to averaging over trials and participants.

Phase synchronization

In addition to local synchronization as reflected by spectral power, between-area synchronization was assessed using the relative phase uniformity as a measure of phase synchronization. We looked at synchronization between left and right M1s and between the EMG signals and M1s (both contra- and ipsilateral hemisphere). The instantaneous Hilbert phase was used to calculate phase differences between pairs of signals. The (circular) variance over time of the phase differences served as a measure of phase locking (Mardia, 1972). This method is identical to the 'phase-locking value' described by Lachaux *et al.* (1999). Unlike the often-employed coherence, these measures of circular statistics are strictly independent from spectral power and hence served as a proper estimate of true phase synchronization (the terms relative phase uniformity and phase synchronization are used as synonyms in this paper). The relative phase uniformity (1 - variance) was calculated for the same frequencies as the spectral power. For the short-duration trials, the variance was taken over trials instead of over time to obtain time-resolved phase synchronization. The same number of trials was used for each subject and condition to avoid any biases in phase uniformity estimates. Corticospinal values were averaged over the three muscles per arm/hand.

Statistics

The average beta activity during the 40-s active period of the continuous force production trials was used to test for differences in activation between conditions. For this, we conducted separate 2×3 repeated-measures ANOVAs for M1 power, EMG power, contra- and ipsilateral M1-EMG and left–right M1 phase synchronization. The main factor 'movement type' (static, dynamic) was the same for all ANOVAs. The three levels of the main factor 'hand' depended on the measure tested. For M1 power, these refer to power in the hemisphere ipsilateral to the active hand, contralateral to the active hand, and bilateral M1s for bimanual force production (ipsilateral, contralateral, bimanual). For EMG power and contra- and ipsilateral M1-EMG phase synchronization the levels refer to whether the hands were producing force (unimanual-passive, unimanual-active, bimanual). A distinction between left and right hand was made in the ANOVA for left–right M1 phase synchronization (unimanual-left, unimanual-right, bimanual). A Greenhouse–Geisser correction was applied whenever Mauchly's test indicated a lack of sphericity. *Post hoc* Bonferroni-adjusted paired-samples *t*-tests were performed whenever a main effect of hand was detected. In addition, for the EMG power and M1-EMG phase synchronization, paired-samples *t*-tests were performed for each active condition compared with resting state. For these latter tests, we indicate the cases for which a significant effect disappears due to a Bonferroni correction for multiple comparisons. We applied a log-transform to the left–right M1 relative phase uniformity values to obtain normally distributed data (as determined with Shapiro–Wilk tests) prior to ANOVA and paired-samples *t*-tests. In addition, a Friedman's ANOVA was performed to the original data. For all tests, we used an α-level of 0.05, and a *P*-value below 0.10 was considered a trend.

For the short-duration trials, we tested for differences between ipsilateral and contralateral beta synchronization patterns during selected time intervals in which ERD (4–5 s) or ERS (6.5–7.5 s) occurred. For each subject, power was averaged within the time interval and the 15–30-Hz frequency band. Paired-samples *t*-tests were conducted for both time intervals separately, and for unimanual as well as bimanual conditions. Again, an α-level of 0.05 was used, and a *P*-value below 0.10 was considered a trend.

Results

All subjects were able after a few practice trials to perform the task without difficulty, and none of them reported muscle fatigue at the end of the experiment.

Beamformers

Significant SAM sources for all conditions are shown in Fig. 2. Only decreases in beta power in bilateral M1 were found. The lack of

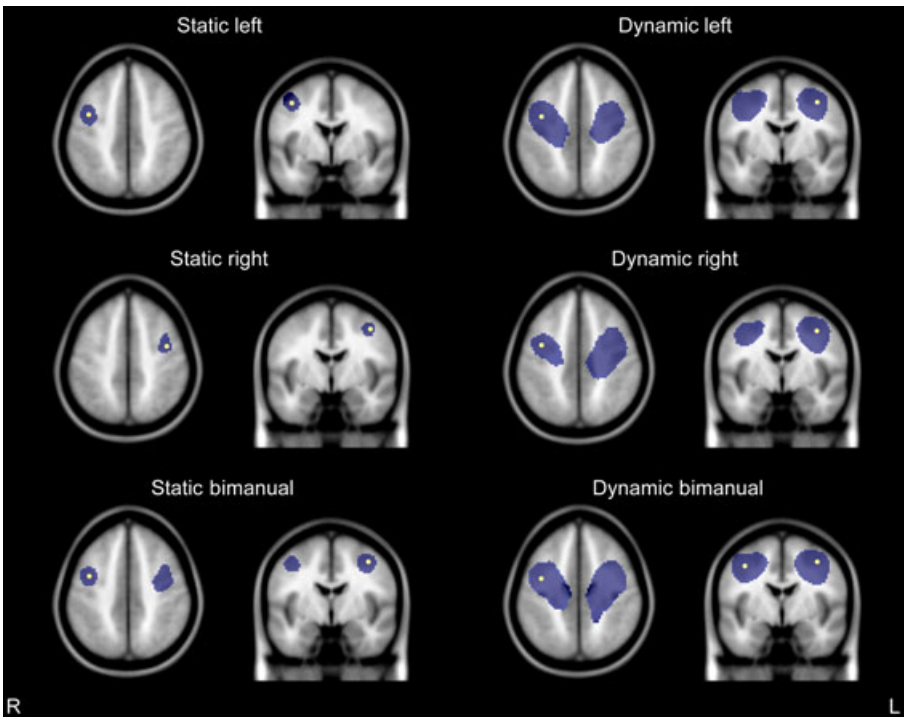

FIG. 2. Beamformer results for all conditions. Voxels for which beta power was significantly decreased on the group level as determined by the permutation tests are highlighted in blue. The yellow dots refer to peak pseudo-*t*-values within each cluster. In case bilateral M1s were activated, the location of RM1 is shown in the axial views and LM1 in the coronal views. Locations did not differ more than 4 mm in the *x*-, *y*- or *z*-directions between conditions.

significant effects in the supplemental motor area (SMA) and other sources was likely due to the non-rhythmicity and simplicity of the tasks (Lang *et al.*, 1990; Gerloff & Andres, 2002). Significant ipsilateral M1 activation during unimanual force production was only present during dynamic conditions. Peak pseudo-*t*-values and number of significant voxels were always larger for dynamic compared with static force production (Table 1). The additionally activated voxels were located primarily in more posterior regions and may reflect a contribution from somatosensory regions.

Continuous force production – power modulations

Grand averaged power in bilateral M1 sources is shown in Fig. 3A. As expected from the beamformer results, beta desynchronization in ipsilateral M1 only occurred during dynamic force production. Also, a significant main effect of 'movement type' indicated that beta desynchronization was overall stronger during dynamic compared with static force production (*F*-statistics and *P*-values of all ANOVAs are summarized in Table 2). In addition, a significant main effect of 'hand' and a significant 'hand × movement type' interaction were found. *Post hoc t*-tests indicated that power for contralateral M1 and during bimanual force production was significantly lower than for ipsilateral M1, but only during static force production. A direct comparison of ipsilateral beta power during unimanual static and dynamic conditions confirmed the stronger desynchronization during dynamic force production (t_{18} = 8.099, $P < 0.001$).

EMG power was high during active force production conditions (Fig. 3B). However, the EMG of the passive hand in the unimanual conditions was also enhanced compared with resting state (static $t_{18} = 2.837$, $P = 0.010$; dynamic $t_{18} = 2.534$, $P = 0.021$), although these effects lost significance after Bonferroni correction for multiple comparisons (number of observations = 6). We found a trend for 'movement type' towards lower power for dynamic conditions. Significant effects were found for 'hand' and the 'hand × movement type' interaction. *Post hoc t*-tests indicated that EMG power differed only between conditions in which force was exerted compared with passive conditions. No difference was found between EMG power of the passive hand in the static and dynamic force conditions ($t_{18} = 0.719$, $P = 0.482$).

TABLE 1. Peak pseudo-*t*-values and cluster sizes of the significant beamformer sources

	Right M1		Left M1	
	Pseudo-*t*	Cluster size (no. of voxels)	Pseudo-*t*	Cluster size (no. of voxels)
Static				
Left hand	−2.00	493		
Right hand			−1.97	248
Bimanual	−2.68	433	−2.25	784
Dynamic				
Left hand	−4.84	3381	−4.73	2711
Right hand	−3.46	1655	−5.15	3886
Bimanual	−4.84	3310	−5.67	3754

M1, primary motor cortex.

Continuous force production – phase synchronization

Relative M1-EMG phase synchronization data for one subject were excluded from statistical tests because they exceeded three standard deviations from the sample mean during static force production.

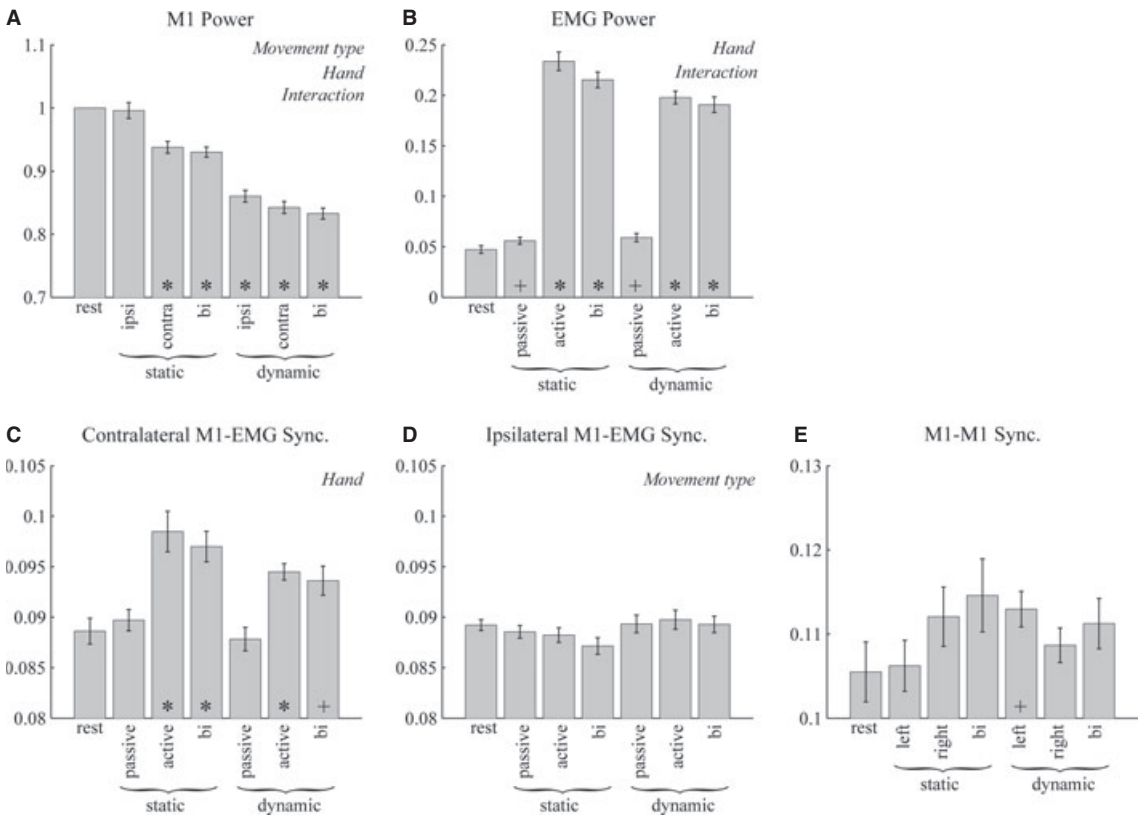

FIG. 3. Mean power (A, B) and phase synchronization (C–E) during continuous force production. For unimanual movements the hemisphere ipsi- and contralateral to the moving hand is denoted by 'ipsi' and 'contra'; 'passive' and 'active' refer to the hand being actively involved in the task; 'left' and 'right' indicate which hand was active during the task. Error bars are corrected for a within-subjects design by setting between-subject variance to zero (Loftus & Masson, 1994). Significant ANOVA effects for each measure are written in the top right corner. Conditions that showed a significant deviation compared with resting state are indicated with a '*', significant deviations that disappear after a Bonferroni correction are indicated with a '+'. Phase synchronization averages are based on 18 subjects (see main text). M1 activity was estimated in source space. EMG, electromyogram; M1, primary motor cortex.

TABLE 2. Results of the 2 × 3 repeated-measures ANOVAs for spectral power and phase synchronization

	Movement type	Hand	Interaction
Power			
M1	**$F_{1,18}$ = 76.317** **P < 0.001**	**$F_{1.396,25.127}$ = 10.713** **P = 0.001**	**$F_{2,36}$ = 6.350** **P = 0.004**
EMG	$F_{1,18}$ = 3.907 P = 0.064	**$F_{2,36}$ = 486.493** **P < 0.001**	**$F_{2,36}$ = 5.875** **P = 0.006**
Phase synchronization			
M1-EMG contralateral	$F_{1,17}$ = 3.811 P = 0.068	**$F_{2,34}$ = 14.044** **P < 0.001**	$F_{2,34}$ = 0.456 P = 0.638
M1-EMG ipsilateral	**$F_{1,17}$ = 4.456** **P = 0.050**	$F_{2,34}$ = 0.394 P = 0.678	$F_{2,34}$ = 0.361 P = 0.700
M1-M1	$F_{1,17}$ = 0.144 P = 0.709	$F_{2,34}$ = 0.470 P = 0.629	$F_{1.482,25.193}$ = 1.836 P = 0.186

Significant effects are indicated in bold. EMG, electromyogram; M1, primary motor cortex.

Results for contralateral and ipsilateral M1-EMG phase synchronization are displayed in Fig. 3C and D, respectively, and F-statistics and P-values of all ANOVAs performed are summarized in Table 2. Contralateral M1-EMG showed a trend for 'movement type', a significant effect of 'hand', but no interaction. *Post hoc* t-tests indicated that phase synchronization was larger for the bimanual and unimanual-active conditions compared with unimanual-passive, and agreed for unimanual-active and bimanual. Compared with resting state, phase synchronization was only larger when force was exerted, of which the effect for bimanual dynamic force production (t_{17} = −2.347, P = 0.031) disappeared with a Bonferroni correction. Although we cannot fully exclude that the increased synchronization levels are influenced by an enhanced signal-to-noise ratio, phase synchronization is expected to rise when the muscles become active, i.e. with higher EMG power.

Ipsilateral M1-EMG phase synchronization showed a significant effect of 'movement type', with lower values for static compared with dynamic force production. When comparing individual conditions to resting state, however, no significant differences were found. The only condition that showed a trend was static-bimanual (t_{17} = 1.983, P = 0.064). No significant effects of 'hand' or 'hand × movement type' interaction were found.

Phase synchronization between M1s was enhanced in all active conditions compared with resting state (Fig. 3E). Compared with resting state, only unimanual-left dynamic force production showed a significant increase (t_{17} = 2.180, P = 0.044, but disappeared with a Bonferroni correction). The corresponding ANOVA did not reveal significant effects. For these parametric tests, the data of one subject were excluded because they exceeded three standard deviations from the sample mean. A non-parametric Friedman's ANOVA with all subjects included did not reveal a significant effect between any of the conditions [$\chi^2(6)$ = 2.549, P = 0.863].

Short-duration trials – event-related power and phase synchronization

Figure 4 displays the dynamics of spectral power in both M1s during the short-duration trials. Beta power decreased (ERD) during the build-up of force and increased (ERS) as soon as force production was held constant. For unimanual movements, the ERD had a similar time course and magnitude in contra- and ipsilateral M1. In contrast, only a clear ERS occurred contralateral to the moving hand. The power in ipsilateral M1 returned to baseline level but did not show a pronounced 'overshoot' as in contralateral M1. This was specific for ipsilateral involvement as the same M1 displayed ERS in the bimanual condition. Statistical comparisons between left and right M1 power within the ERD and ERS time intervals indicated only a significant difference for ERS in the unimanual condition ($t_{18} = 3.483$, $P = 0.003$).

Corticospinal M1-EMG synchronization was only present during static force production, and only when the hand was actively involved in the task (Fig. 5). No modulations in ipsilateral M1-EMG and left–right M1 phase synchronization were observed.

Discussion

We investigated the functional role of beta oscillations in ipsilateral M1 during unimanual force production under continuous static and dynamic conditions, as well as in an event-related design. A movement-related power decrease was only found during dynamic force production, which did not result in increased muscle activation or M1-EMG synchronization. Synchronization between M1s was enhanced compared with resting state across conditions, but did not reach significance. Furthermore, ERD was bilaterally modulated during unimanual movement, whereas ERS exceeded baseline only in contralateral M1. These findings suggest that ipsilateral M1 activity not only reflects mere cross-talk effects but also additional means for achieving proper motor control, hence confirming our hypothesis. In the following, we provide a possible explanation for these observed beta modulations in ipsilateral M1. In doing so, we discuss our results against the background of recent functional (f)MRI and transcranial magnetic stimulation (TMS) studies with emphasis on interhemispheric facilitation vs. inhibitory mechanisms.

Indications for distinct neural mechanisms underlying beta desynchronization in contra- and ipsilateral motor cortex

Decreased beta power in both contra- and ipsilateral motor areas during (rhythmic) motor behavior has been reported in several studies (Salmelin *et al.*, 1995; Manganotti *et al.*, 1998; Hummel *et al.*, 2003; Gross *et al.*, 2005; Houweling *et al.*, 2008). Although the suppression appears stronger in the contralateral hemisphere, bilateral M1s show a comparable modulation. In contrast, fMRI studies revealed markedly different blood oxygen level-dependent (BOLD) responses in contra- and ipsilateral M1 – positive BOLD responses in contralateral M1 and

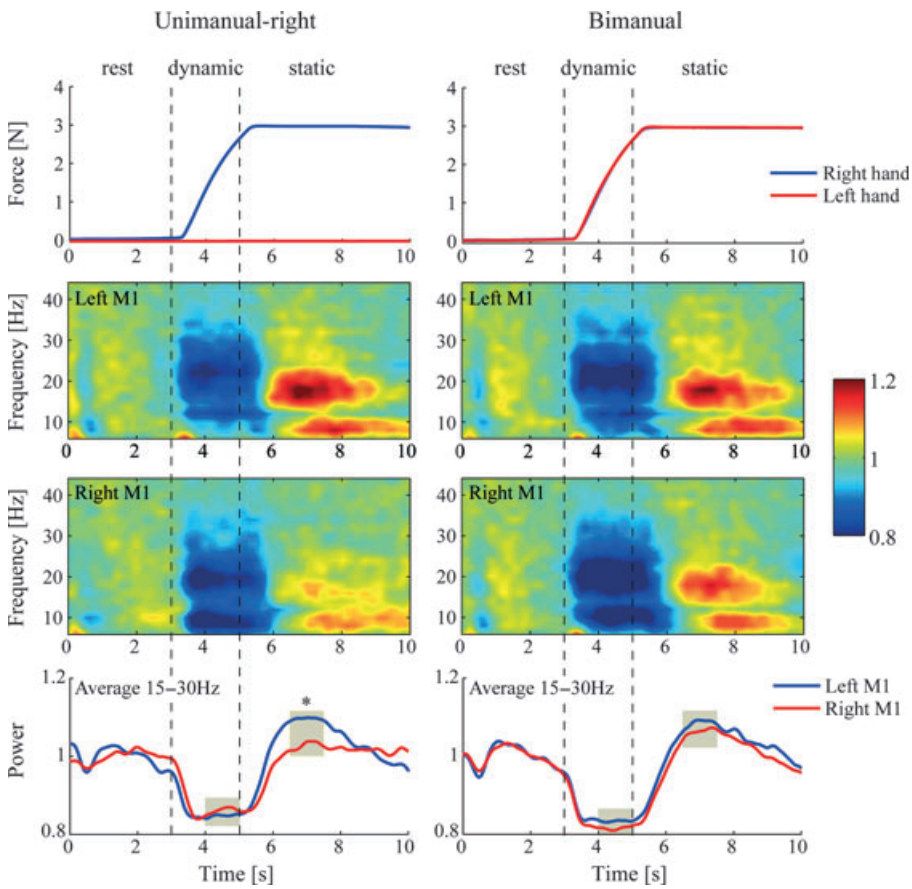

FIG. 4. Force profiles and event-related changes in primary motor cortex (M1) power. Force increased during the dynamic interval and was held constant during the static interval (top panels). Middle panels show the time–frequency power spectra of left and right M1. The mean power in the resting state interval served as a baseline for normalization. Bottom panels show grand average beta power. The gray patches indicate the time intervals that were tested for significant differences in power between left and right M1. The only significant difference was found for ERS in the unimanual-right condition, indicated with a '*'. This was caused by the absence of a marked ipsilateral ERS exceeding baseline level. M1 activity was estimated in source space.

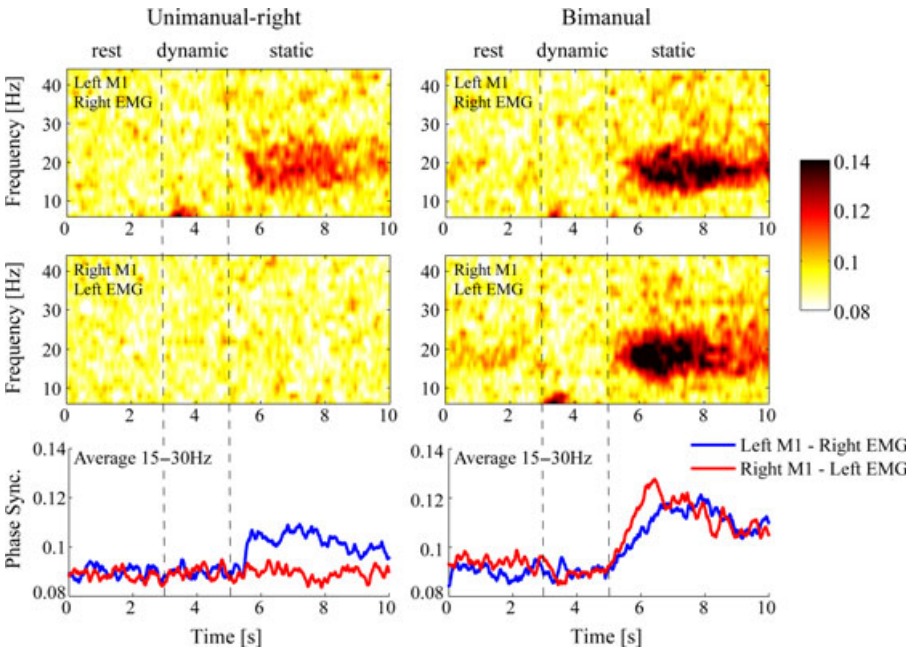

FIG. 5. Event-related changes in contralateral primary motor cortex (M1)-electromyogram (EMG) phase synchronization (cf. Fig. 4). Only when the hand was performing static force production did phase synchronization increase. No modulations were found in ipsilateral M1-EMG phase synchronization (not shown). M1 activity was estimated in source space.

negative ones in ipsilateral M1 (Allison *et al.*, 2000; Nirkko *et al.*, 2001; Hamzei *et al.*, 2002; Stefanovic *et al.*, 2004; Newton *et al.*, 2005; Hayashi *et al.*, 2008). Interestingly, the negative ipsilateral BOLD response in M1 represents a reduced metabolism that has been interpreted as a decrease or 'inhibition' of activation (Stefanovic *et al.*, 2004); we note, however, that the interpretation of the BOLD signal in terms of neural activity is far from straightforward (Logothetis, 2008).

Reconciling the bilateral beta desynchronization in our experiments with the modulations in BOLD response in contra- and ipsilateral hemisphere requires an account of the neurophysiological origin of oscillatory activity recorded with MEG/electroencephalography (EEG). Rather than neural spikes, M/EEG picks up intra-/extracellular currents related to postsynaptic potentials on the dendrites of spatially aligned pyramidal cells, lumped over a large neural population. Moreover, it is impossible to discriminate between postsynaptic inhibitory and excitatory potentials, and hence to determine whether summation of postsynaptic potentials led to neural firing (Buzsáki, 2006). Measured spectral M/EEG power may drop when less postsynaptic activity takes place, but also when the timing of postsynaptic potentials within the population is more asynchronous. Invasive recordings in the macaque contralateral M1 showed a positive correlation between beta desynchronization and firing rate of pyramidal tract neurons during movement (Baker *et al.*, 2001; Spinks *et al.*, 2008). In contrast, the negative BOLD response suggests that ipsilateral beta desynchronization may be caused by a mere decrease in neural activity.

Interhemispheric facilitation vis-à-vis inhibition

Both interhemispheric facilitation and inhibition have been observed by testing the excitability of ipsilateral M1 using TMS. The amplitude of motor-evoked potentials (MEPs) elicited with TMS over contralateral M1 increases when, at the same time, the other hand performs static muscle contractions (Hess *et al.*, 1987; Stedman *et al.*, 1998; Muellbacher *et al.*, 2000; Liepert *et al.*, 2001). For rhythmic muscle contractions the excitability is modulated by the phase of the movement cycle (Stinear & Byblow, 2002; Carson *et al.*, 2004) and may even become inhibitory (Liepert *et al.*, 2001; Sohn *et al.*, 2003). Direct transcallosal interactions have been tested using a paired-pulse paradigm where single TMS stimuli are applied to both M1s separated by a short time interval. Depending on latency this either results in a facilitation (1–5 ms) or inhibition (6–20 ms) of the corticospinal excitability in the hemisphere receiving the second pulse (Ferbert *et al.*, 1992; Salerno & Georgesco, 1996; Gerloff *et al.*, 1998a; Hanajima *et al.*, 2001; Hoy *et al.*, 2008).

Premotor areas may play a mediating role in suppressing mirror movements through interhemispheric inhibition. More precisely, the actual inhibition of ipsilateral M1 occurs intrahemispherically, as excitatory transcallosal projections from contralateral motor areas activate ipsilateral interneurons, which in turn inhibit corticospinal neurons (Daffertshofer *et al.*, 2005). This idea finds support when hampering normal functioning of ipsilateral premotor cortex using repetitive TMS (rTMS), which results in an increased correlation in activity between left and right M1 during unimanual movements (Verstynen & Ivry, 2011). Similarly, rTMS applied over contralateral premotor cortex can enhance the excitability of ipsilateral M1, whereas a single pulse yields converse effects (Cincotta *et al.*, 2004). In fact, the involvement of ipsilateral premotor areas during unimanual movement has been established in fMRI experiments. In addition to the aforementioned negative BOLD responses in ipsilateral M1, there are several studies that report increased BOLD in the ipsilateral hemisphere, which have been attributed to secondary motor areas, including the premotor cortex and SMA (Cramer *et al.*, 1999; Nirkko *et al.*, 2001; Hanakawa *et al.*, 2005; Verstynen *et al.*, 2005; Horenstein *et al.*, 2009; Verstynen & Ivry, 2011). In the present study, peak locations of left and right M1 during contra- and ipsilateral unimanual dynamic force production were identical, implying activation of homologous neural structures.

Interhemispheric facilitation should become apparent in the phase synchronization between left and right M1s, but we did not find any

significant effects. Reports in the literature of M1–M1 entrainment are scarce, although some evidence in favor of statistically significant bilateral entrainment can be found (Gerloff *et al.*, 1998b; Mima *et al.*, 2000; Gross *et al.*, 2005). Perhaps the occurrence of high-frequency synchronization in these studies is related to the rhythmicity of the employed motor tasks and the accompanying involvement of SMA. The lack of significant M1–M1 synchrony in the present study could also result from the involvement of two (or more) distinct neural mechanisms. That is, both ipsi- and contralateral M1 are active but no bilateral synchronization emerges because different neuronal activity patterns bring about the beta desynchronization.

Differential ipsilateral activation for static and dynamic force production

The reason why beta power in ipsilateral M1 significantly decreases during unimanual dynamic but not during static force production might be directly related to the degree of contralateral activation. Despite the lower average force production during the dynamic compared with static conditions, beta desynchronization was much stronger and comprised a larger number of significantly activated voxels, in line with fMRI observations (Thickbroom *et al.*, 1999; Keisker *et al.*, 2010). Compared with static muscle contractions, dynamic force production involves a continuous change in motor output that requires more movement parameters to be controlled as well as accurate timing. As a consequence, interhemispheric cross-talk might be both larger and also harder to suppress, possibly leading to the observed larger beta desynchronization in ipsilateral hemisphere.

ERD/ERS and corticospinal excitability

Studying corticospinal excitability during different phases of event-related ipsilateral beta modulations might give more insight into inhibitory and facilitatory mechanisms. By combining TMS and EEG, Rau *et al.* (2003) found that in unimanual phasic finger movements the excitability of ipsilateral M1 during beta desynchronization was increased (by means of increased MEPs). This effect did not last for the entire time interval during which ipsilateral ERD was present, but was confined to the duration of the EMG burst of the moving finger. Paired-pulse TMS revealed that the increased corticospinal excitability was caused by (or at least related to) increased interhemispheric facilitation. In contrast, no change in excitability was found during ERS, which is associated with a decrease in corticospinal excitability in contralateral M1 (Chen *et al.*, 1998) and inhibition of movement initiation (Gilbertson *et al.*, 2005; Androulidakis *et al.*, 2007; Zhang *et al.*, 2008; van Wijk *et al.*, 2009).

Unlike bilateral ERD, post-movement ERS only occurred after contralateral hand movement. Ipsilateral beta power increases after movement termination, but an overshoot compared with baseline level has been found to be diminished (Salmelin *et al.*, 1995; Stancak *et al.*, 1997) or even entirely absent (Alegre *et al.*, 2003; Erbil & Ungan, 2007); when present, it is not coherent with contralateral ERS (Andrew & Pfurtscheller, 1999). Considering the positive correlation between beta desynchronization and firing rate of pyramidal tract neurons during movement (Baker *et al.*, 2001; Spinks *et al.*, 2008), post-movement beta synchronization might reflect a deactivation of pyramidal cells and restoration of resting state oscillations. Restoration of ipsilateral deactivation of neural activity might give rise to different synchronization patterns than the reduction in firing rate of contralateral pyramidal tract neurons.

Modulations of corticospinal synchronization

Event-related contralateral M1-EMG synchronization is typically absent during increases in force production, but builds up when force is held constant (Kilner *et al.*, 2000, 2003), and might even arise directly after transient movements (Feige *et al.*, 2000). Increased levels are generally also found when averaging over a time interval of rhythmic or static motor behavior (Conway *et al.*, 1995; Salenius *et al.*, 1997; Gross *et al.*, 2005; Chakarov *et al.*, 2009). Our findings regarding contralateral M1-EMG phase synchronization are in line with these observations and hence did not come as a surprise. However, we did not anticipate the significant main effect of 'movement type' for ipsilateral M1-EMG synchronization. Synchronization was diminished during static force production and enhanced during dynamic force production. It seems that during static force production, cortical output to the spinal cord via ipsilateral pathways may be suppressed, unlike during dynamic force production. This would resemble the stronger interhemispheric cross-talk for dynamic compared with static force conditions. However, the size of this effect seems only weak as no significant differences with resting state were found. A clear-cut explanation for the modulation of corticospinal synchronization hence remains remote.

Conclusion

Modulations of ipsilateral M1 beta power during unimanual force production do not fully resemble those of contralateral M1. Therefore, ipsilateral activity does not solely stem from an interhemispheric cross-talk but seems to reflect additional neural mechanisms that can be related to inhibition of motor output. Identification of the (distinct) neural processes underlying the observed bilateral beta desynchronization likely requires future research to include invasive techniques assessing local field potentials and spike activity in ipsi- and contralateral M1.

Acknowledgements

We thank Bert Clairbois and Bert Coolen for their technical support. This work was supported by The Netherlands Organisation for Scientific Research (grant number 021-002-047).

Abbreviations

BOLD, blood oxygen level-dependent; EEG, electroencephalography; EMG, electromyography; ERD, event-related desynchronization; ERS, event-related synchronization; fMRI, functional magnetic resonance imaging; M1, primary motor cortex; MEG, magnetoencephalography; MEP, motor-evoked potential; MRI, magnetic resonance imaging; rTMS, repetitive transcranial magnetic stimulation; SAM, synthetic aperture magnetronomy; SMA, supplemental motor area; TMS, transcranial magnetic stimulation.

References

Alegre, M., Labarga, A., Gurtubay, I.G., Iriarte, J., Malanda, A. & Artieda, J. (2003) Movement-related changes in cortical oscillatory activity in ballistic, sustained and negative movements. *Exp. Brain Res.*, **148**, 17–25.

Allison, J.D., Meader, K.J., Loring, D.W., Figueroa, R.E. & Wright, J.C. (2000) Functional MRI cerebral activation and deactivation during finger movement. *Neurology*, **54**, 135–142.

Andrew, C. & Pfurtscheller, G. (1999) Lack of bilateral coherence of post-movement central beta oscillations in the human electroencephalogram. *Neurosci. Lett.*, **273**, 89–92.

Androulidakis, A.G., Doyle, L.M.F., Yarrow, K., Litvak, V., Gilbertson, T.P. & Brown, P. (2007) Anticipatory changes in beta synchrony in the human

corticospinal system and associated improvements in task performance. *Eur. J. Neurosci.*, **25**, 3758–3765.
Aramaki, Y., Honda, M., Okada, T. & Sadato, N. (2006) Neural correlates of the spontaneous phase transition during bimanual coordination. *Cereb. Cortex*, **16**, 1338–1348.
Aranyi, Z. & Rosler, K.M. (2002) Effort-induced mirror movements. A study of transcallosal inhibition in humans. *Exp. Brain Res.*, **145**, 76–82.
Armatas, C.A., Summers, J.J. & Bradshaw, J.L. (1994) Mirror movements in normal adult subjects. *J. Clin. Exp. Neuropsychol.*, **16**, 405–413.
Babiloni, C., Carducci, F., Pizzella, V., Indovina, I., Romani, G.L., Rossini, P.M. & Babiloni, F. (1999) Bilateral neuromagnetic activation of human primary sensorimotor cortex in preparation and execution of unilateral voluntary finger movements. *Brain Res.*, **827**, 234–236.
Baker, S.N., Spinks, R., Jackson, A. & Lemon, R.N. (2001) Synchronization in monkey motor cortex during a precision grip task. I. Task-dependent modulation in single-unit synchrony. *J. Neurophysiol.*, **85**, 869–885.
Baraldi, P., Porro, C.A., Serafini, M., Pagnoni, G., Murari, C., Corazza, R. & Nichelli, P. (1999) Bilateral representation of sequential finger movements in human cortical areas. *Neurosci. Lett.*, **269**, 95–98.
Buzsáki, G. (2006) *Rhythms of the Brain*. Oxford University Press, Oxford.
Carson, R.G. (2005) Neural pathways mediating bilateral interactions between the upper limbs. *Brain Res. Rev.*, **49**, 641–662.
Carson, R.G., Riek, S., Mackey, D.C., Meichenbaum, D.P., Willms, K., Forner, M. & Byblow, W.D. (2004) Excitability changes in human forearm corticospinal projections and spinal reflex pathways during rhythmic voluntary movement of the opposite limb. *J. Physiol. (Lond.)*, **560**, 929–940.
Chakarov, V., Naranjo, J.R., Schulte-Monting, J., Omlor, W., Huethe, F. & Kristeva, R. (2009) Beta-range EEG-EMG coherence with isometric compensation for increasing modulated low-level forces. *J. Neurophysiol.*, **102**, 1115–1120.
Chen, R., Yaseen, Z., Cohen, L.G. & Hallett, M. (1998) Time course of corticospinal excitability in reaction time and self-paced movements. *Ann. Neurol.*, **44**, 317–325.
Cheyne, D., Bakhtazad, L. & Gaetz, W. (2006) Spatiotemporal mapping of cortical activity accompanying voluntary movements using an event-related beamforming approach. *Hum. Brain Mapp.*, **27**, 213–229.
Cincotta, M. & Ziemann, U. (2008) Neurophysiology of unimanual motor control and mirror movements. *Clin. Neurophysiol.*, **119**, 744–762.
Cincotta, M., Borgheresi, A., Balestrieri, F., Giovannelli, F., Rossi, S., Ragazzoni, A., Zaccara, G. & Ziemann, U. (2004) Involvement of the human dorsal premotor cortex in unimanual motor control: an interference approach using transcranial magnetic stimulation. *Neurosci. Lett.*, **367**, 189–193.
Conway, B.A., Halliday, D.M., Farmer, S.F., Shahani, U., Maas, P., Weir, A.I. & Rosenberg, J.R. (1995) Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man. *J. Physiol. (Lond.)*, **489**, 917–924.
Cramer, S.C., Finklestein, S.P., Schaechter, J.D., Bush, G. & Rosen, B.R. (1999) Activation of distinct motor cortex regions during ipsilateral and contralateral finger movements. *J. Neurophysiol.*, **81**, 383–387.
Daffertshofer, A., van den Berg, C. & Beek, P.J. (1999) A dynamical model for mirror movements. *Physica D*, **132**, 243–266.
Daffertshofer, A., Peper, C.E. & Beek, P.J. (2005) Stabilization of bimanual coordination due to active interhemispheric inhibition: a dynamical account. *Biol. Cybern.*, **92**, 101–109.
Erbil, N. & Ungan, P. (2007) Changes in the alpha and beta amplitudes of the central EEG during the onset, continuation, and offset of long-duration repetitive hand movements. *Brain Res.*, **1169**, 44–56.
Feige, B., Aertsen, A. & Kristeva-Feige, R. (2000) Dynamic synchronization between multiple cortical motor areas and muscle activity in phasic voluntary movements. *J. Neurophysiol.*, **84**, 2622–2629.
Ferbert, A., Priori, A., Rothwell, J.C., Day, B.L., Colebatch, J.G. & Marsden, C.D. (1992) Interhemispheric inhibition of the human motor cortex. *J. Physiol. (Lond.)*, **453**, 525–546.
Gerloff, C. & Andres, F.G. (2002) Bimanual coordination and interhemispheric interaction. *Acta Psychol. (Amst.)*, **110**, 161–186.
Gerloff, C., Cohen, L.G., Floeter, M.K., Chen, R., Corwell, B. & Hallett, M. (1998a) Inhibitory influence of the ipsilateral motor cortex on responses to stimulation of the human cortex and pyramidal tract. *J. Physiol. (Lond.)*, **510**, 249–259.
Gerloff, C., Richard, J., Hadley, J., Schulman, A.E., Honda, M. & Hallett, M. (1998b) Functional coupling and regional activation of human cortical motor areas during simple, internally paced and externally paced finger movements. *Brain*, **121**, 1513–1531.
Gilbertson, T., Lalo, E., Doyle, L., Di Lazzaro, V., Cioni, B. & Brown, P. (2005) Existing motor state is favored at the expense of new movement during 13–35 Hz oscillatory synchrony in the human corticospinal system. *J. Neurosci.*, **25**, 7771–7779.
Gross, J., Pollok, B., Dirks, M., Timmermann, L., Butz, M. & Schnitzler, A. (2005) Task-dependent oscillations during unimanual and bimanual movements in the human primary motor cortex and SMA studied with magnetoencephalography. *Neuroimage*, **26**, 91–98.
Halliday, D.M., Rosenberg, J.R., Amjad, A.M., Breeze, P., Conway, B.A. & Farmer, S.F. (1995) A framework for the analysis of mixed time series/point process data – theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Prog. Biophys. Mol. Biol.*, **64**, 237–278.
Hamzei, F., Dettmers, C., Rzanny, R., Liepert, J., Buchel, C. & Weiller, C. (2002) Reduction of excitability (''inhibition'') in the ipsilateral primary motor cortex is mirrored by fMRI signal decreases. *Neuroimage*, **17**, 490–496.
Hanajima, R., Ugawa, Y., Machii, K., Mochizuki, H., Terao, Y., Enomoto, H., Furubayashi, T., Shiio, Y., Uesugi, H. & Kanazawa, I. (2001) Interhemispheric facilitation of the hand motor area in humans. *J. Physiol. (Lond.)*, **531**, 849–859.
Hanakawa, T., Parikh, S., Bruno, M.K. & Hallett, M. (2005) Finger and face representations in the ipsilateral precentral motor areas in humans. *J. Neurophysiol.*, **93**, 2950–2958.
Hayashi, M.J., Saito, D.N., Aramaki, Y., Asai, T., Fujibayashi, Y. & Sadato, N. (2008) Hemispheric asymmetry of frequency-dependent suppression in the ipsilateral primary motor cortex during finger movement: a functional magnetic resonance imaging study. *Cereb. Cortex*, **18**, 2932–2940.
Hess, C.W., Mills, K.R. & Murray, N.M.F. (1987) Responses in small hand muscles from magnetic stimulation of the human brain. *J. Physiol. (Lond.)*, **388**, 397–419.
Hillebrand, A. & Barnes, G.R. (2005) Beamformer analysis of MEG data. *Int. Rev. Neurobiol.*, **68**, 149–171.
Horenstein, C., Lowe, M.J., Koenig, K.A. & Phillips, M.D. (2009) Comparison of unilateral and bilateral complex finger tapping-related activation in premotor and primary motor cortex. *Hum. Brain Mapp.*, **30**, 1397–1412.
Houweling, S., Daffertshofer, A., van Dijk, B.W. & Beek, P.J. (2008) Neural changes induced by learning a challenging perceptual-motor task. *Neuroimage*, **41**, 1395–1407.
Houweling, S., Beek, P.J. & Daffertshofer, A. (2010) Spectral changes of interhemispheric crosstalk during movement instabilities. *Cereb. Cortex*, **20**, 2605–2613.
Hoy, K.E., Fitzgerald, P.B., Bradshaw, J.L., Armatas, C.A. & Georgiou-Karistianis, N. (2004) Investigating the cortical origins of motor overflow. *Brain Res. Brain Res. Rev.*, **46**, 315–327.
Hoy, K.E., Georgiou-Karistianis, N., Layeock, R. & Fitzgerald, P.B. (2008) A transcranial magnetic stimulation study of transcallosal inhibition and facilitation in schizophrenia. *J. Clin. Neurosci.*, **15**, 863–867.
Huang, M.X., Harrington, D.L., Paulson, K.M., Weisend, M.P. & Lee, R.R. (2004) Temporal dynamics of ipsilateral and contralateral motor activity during voluntary finger movement. *Hum. Brain Mapp.*, **23**, 26–39.
Hubers, A., Orekhov, Y. & Ziemann, U. (2008) Interhemispheric motor inhibition: its role in controlling electromyographic mirror activity. *Eur. J. Neurosci.*, **28**, 364–371.
Hummel, F., Kirsammer, R. & Gerloff, C. (2003) Ipsilateral cortical activation during finger sequences of increasing complexity: representation of movement difficulty or memory load? *Clin. Neurophysiol.*, **114**, 605–613.
Immisch, I., Waldvogel, D., van Gelderen, P. & Hallett, M. (2001) The role of the medial wall and its anatomical variations for bimanual antiphase and in-phase movements. *Neuroimage*, **14**, 674–684.
Keisker, B., Hepp-Reymond, M.C., Blickenstorfer, A. & Kollias, S.S. (2010) Differential representation of dynamic and static power grip force in the sensorimotor network. *Eur. J. Neurosci.*, **31**, 1483–1491.
Kilner, J.M., Baker, S.N., Salenius, S., Hari, R. & Lemon, R.N. (2000) Human cortical muscle coherence is directly related to specific motor parameters. *J. Neurosci.*, **20**, 8838–8845.
Kilner, J.M., Salenius, S., Baker, S.N., Jackson, A., Hari, R. & Lemon, R.N. (2003) Task-dependent modulations of cortical oscillatory activity in human subjects during a bimanual precision grip task. *Neuroimage*, **18**, 67–73.
Kristeva, R., Keller, E., Deecke, L. & Kornhuber, H.H. (1979) Cerebral potentials preceding unilateral and simultaneous bilateral finger movements. *Electroencephalogr. Clin. Neurophysiol.*, **47**, 229–238.
Kristeva, R., Cheyne, D. & Deecke, L. (1991) Neuromagnetic fields accompanying unilateral and bilateral voluntary movements – topography and analysis of cortical sources. *Electroencephalogr. Clin. Neurophysiol.*, **81**, 284–298.
Lachaux, J.P., Rodriguez, E., Martinerie, J. & Varela, F.J. (1999) Measuring phase synchrony in brain signals. *Hum. Brain Mapp.*, **8**, 194–208.

Lang, W., Obrig, H., Lindinger, G., Cheyne, D. & Deecke, L. (1990) Supplementary motor area activation while tapping bimanually different rhythms in musicians. *Exp. Brain Res.*, **79**, 504–514.
Liepert, J., Dettmers, C., Terborg, C. & Weiller, C. (2001) Inhibition of ipsilateral motor cortex during phasic generation of low force. *Clin. Neurophysiol.*, **112**, 114–121.
Loftus, G.R. & Masson, M.E.J. (1994) Using confidence-intervals in within-subject designs. *Psychon. Bull. Rev.*, **1**, 476–490.
Logothetis, N.K. (2008) What we can do and what we cannot do with fMRI. *Nature*, **453**, 869–878.
Manganotti, P., Gerloff, C., Toro, C., Katsuta, H., Sadato, N., Zhuang, P., Leocani, L. & Hallett, M. (1998) Task-related coherence and task-related spectral power changes during sequential finger movements. *Eklectromyogr. Motor C*, **109**, 50–62.
Mardia, K.V. (1972) *Statistics of Directional Data*. Academic Press, London, New York.
Mayston, M.J., Harrison, L.M. & Stephens, J.A. (1999) A neurophysiological study of mirror movements in adults and children. *Ann. Neurol.*, **45**, 583–594.
Mima, T., Matsuoka, T. & Hallett, M. (2000) Functional coupling of human right and left cortical motor areas demonstrated with partial coherence analysis. *Neurosci. Lett.*, **287**, 93–96.
Muellbacher, W., Facchini, S., Boroojerdi, B. & Hallett, M. (2000) Changes in motor cortex excitability during ipsilateral hand muscle activation in humans. *Clin. Neurophysiol.*, **111**, 344–349.
de Munck, J.C., Verbunt, J.P.A., Van't Ent, D. & van Dijk, B.W. (2001) The use of an MEG device as 3D digitizer and motion monitoring system. *Phys. Med. Biol.*, **46**, 2041–2052.
Myers, L.J., Lowery, M., O'Malley, M., Vaughan, C.L., Heneghan, C., St Clair, G.A., Harley, Y.X. & Sreenivasan, R. (2003) Rectification and non-linear pre-processing of EMG signals for cortico-muscular analysis. *J. Neurosci. Methods*, **124**, 157–165.
Newton, J.M., Sunderland, A. & Gowland, P.A. (2005) fMRI signal decreases in ipsilateral primary motor cortex during unilateral hand movements are related to duration and side of movement. *Neuroimage*, **24**, 1080–1087.
Nichols, T.E. & Holmes, A.P. (2002) Nonparametric permutation tests for functional neuroimaging: a primer with examples. *Hum. Brain Mapp.*, **15**, 1–25.
Nirkko, A.C., Ozdoba, C., Redmond, S.M., Burki, M., Schroth, G., Hess, C.W. & Wiesendanger, M. (2001) Different ipsilateral representations for distal and proximal movements in the sensorimotor cortex: activation and deactivation patterns. *Neuroimage*, **13**, 825–835.
Oldfield, R.C. (1971) Assessment and analysis of handedness – Edinburgh Inventory. *Neuropsychologia*, **9**, 97–113.
Rau, C., Plewnia, C., Hummel, F. & Gerloff, C. (2003) Event-related desynchronization and excitability of the ipsilateral motor cortex during simple self-paced finger movements. *Clin. Neurophysiol.*, **114**, 1819–1826.
Sadato, N., Yonekura, Y., Waki, A., Yamada, H. & Ishii, Y. (1997) Role of the supplementary motor area and the right premotor cortex in the coordination of bimanual finger movements. *J. Neurosci.*, **17**, 9667–9674.
Salenius, S., Portin, K., Kajola, M., Salmelin, R. & Hari, R. (1997) Cortical control of human motoneuron firing during isometric contraction. *J. Neurophysiol.*, **77**, 3401–3405.
Salerno, A. & Georgesco, M. (1996) Interhemispheric facilitation and inhibition studied in man with double magnetic stimulation. *Eklectromyogr. Motor C*, **101**, 395–403.
Salmelin, R., Forss, N., Knuutila, J. & Hari, R. (1995) Bilateral activation of the human somatomotor cortex by distal hand movements. *Electroencephalogr. Clin. Neurophysiol.*, **95**, 444–452.
Singh, K.D., Barnes, G.R. & Hillebrand, A. (2003) Group imaging of task-related changes in cortical synchronisation using nonparametric permutation testing. *Neuroimage*, **19**, 1589–1601.
Sohn, Y.H., Jung, H.Y., Kaelin-Lang, A. & Hallett, M. (2003) Excitability of the ipsilateral motor cortex during phasic voluntary hand movement. *Exp. Brain Res.*, **148**, 176–185.
Spinks, R.L., Kraskov, A., Brochier, T., Umilta, M.A. & Lemon, R.N. (2008) Selectivity for grasp in local field potential and single neuron activity recorded simultaneously from M1 and F5 in the awake macaque monkey. *J. Neurosci.*, **28**, 10961–10971.
Stancak, A., Riml, A. & Pfurtscheller, G. (1997) The effects of external load on movement-related changes of the sensorimotor EEG rhythms. *Electroencephalogr. Clin. Neurophysiol.*, **102**, 495–504.
Stedman, A., Davey, N.J. & Ellaway, P.H. (1998) Facilitation of human first dorsal interosseous muscle responses to transcranial magnetic stimulation during voluntary contraction of the contralateral homonymous muscle. *Muscle Nerve*, **21**, 1033–1039.
Stefanovic, B., Warnking, J.M. & Pike, G.B. (2004) Hemodynamic and metabolic responses to neuronal inhibition. *Neuroimage*, **22**, 771–778.
Steinstraeter, O., Teismann, I.K., Wollbrink, A., Suntrup, S., Stoeckigt, K., Dziewas, R. & Pantev, C. (2009) Local sphere-based co-registration for SAM group analysis in subjects without individual MRI. *Exp. Brain Res.*, **193**, 387–396.
Stephan, K.M., Binkofski, F., Posse, S., Seitz, R.J. & Freund, H.J. (1999) Cerebral midline structures in bimanual coordination. *Exp. Brain Res.*, **128**, 243–249.
Stinear, J.W. & Byblow, W.D. (2002) Disinhibition in the human motor cortex is enhanced by synchronous upper limb movements. *J. Physiol. (Lond.)*, **543**, 307–316.
Thickbroom, G.W., Phillips, B.A., Morris, I., Byrnes, M.L., Sacco, P. & Mastaglia, F.L. (1999) Differences in functional magnetic resonance imaging of sensorimotor cortex during static and dynamic finger flexion. *Exp. Brain Res.*, **126**, 431–438.
Verstynen, T. & Ivry, R.B. (2011) Network dynamics mediating ipsilateral motor cortex activity during unimanual actions. *J. Cogn. Neurosci*, **23**, 2468–2480.
Verstynen, T., Diedrichsen, J., Albert, N., Aparicio, P. & Ivry, R.B. (2005) Ipsilateral motor cortex activity during unimanual hand movements relates to task complexity. *J. Neurophysiol.*, **93**, 1209–1222.
Vrba, J. & Robinson, S.E. (2001) Signal processing in magnetoencephalography. *Methods*, **25**, 249–271.
van Wijk, B.C.M., Daffertshofer, A., Roach, N. & Praamstra, P. (2009) A role of beta oscillatory synchrony in biasing response competition? *Cereb. Cortex*, **19**, 1294–1302.
Zhang, Y., Chen, Y., Bressler, S.L. & Ding, M. (2008) Response preparation and inhibition: the role of the cortical sensorimotor beta rhythm. *Neuroscience*, **156**, 238–246.